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On Nulling Interferometers and the Line-Emitting Regions of AGNs

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ABSTRACT

The nulling interferometers proposed to study planets around other stars are generally well suited for studying small-scale structures surrounding other bright pointlike objects such as the nuclei of active galaxies. Conventional interferometric techniques will produce useful maps of optical/IR line and continuum emission within active galaxies on scales of 10 milliarcseconds (mas), but similar studies of broad-line regions will require baselines longer than those currently envisaged. Nevertheless, nulling interferometers currently under development will be able to constrain quasar velocity fields on ~ 1 mas scales, as long as they are equipped with spectrographs capable of resolving lines several hundred km s^{-1} wide. This *Letter* describes how analyses of line emission leaking through the edges of the null in such an instrument can reveal the size, shape, and velocity field of nebular gas on the outskirts of a quasar broad-line region. If this technique proves effective, it could potentially be used to measure the mass function of quasar black holes throughout the universe.

Subject headings: galaxies: active — quasars: emission lines — techniques: interferometric

1. Introduction

Nulling interferometry, a technique inspired by the desire to study extrasolar planets, appears ready to blossom into a practical astronomical tool in the coming decades (Allen, Peterson, & Shao 1997; Angel & Woolf 1997). The most basic nulling interferometer would consist of two identical telescopes and a beam combiner that inverts the phase of one telescope's signal before adding it to the other (Bracewell 1978; Bracewell & Macphie 1979; Shao & Colavita 1992). If active delay lines can equalize all the pathlengths in the optical system, the signal from a pointlike object in the symmetry plane between the two telescopes will cancel at all wavelengths.

The signal cancelling capability of nulling interferometers makes them ideal for observing planets around nearby stars, as well as other sources less than an arcsecond from a bright object.

These devices will be excellent for studying the narrow-line regions of active galaxies. Maps of the $2 - 10\mu\text{m}$ emission around active galactic nuclei (AGNs) will help resolve questions ranging from the role of starbursts in AGNs to the anisotropy of their UV emission (Miley 1997; Voit 1997a,b; Ward 1997). Even without nulling, ground-based continuum observations will easily resolve the thermal emission from 300 K material, because active optical correction of large telescopes is relatively simple at $10\mu\text{m}$.

Broad-line regions of AGNs present a greater challenge. Their typical sizes, a few milliarcseconds or less, are somewhat smaller than the smallest beamsizes currently proposed for optical/IR interferometers. The Keck and Very Large Telescope (VLT) interferometers, with baselines $\sim 100\text{ m}$, will have beamsizes $\sim 4\text{ mas}$ at $2\mu\text{m}$. The Space Interferometry Mission (SIM), slated to operate in the optical band, envisions a baseline of 10 m , giving a minimum beamsize $\sim 10\text{ mas}$. Although SIM’s nominal beamsize is somewhat larger, its position above the Earth’s distorting atmosphere makes it especially useful for nulling observations, which require precise management of the total optical path from the source through the instrument.

Despite these beamsizes, nulling interferometers might still yield unique information about the broad-line regions of AGNs, if we tailor the instruments properly and keep our goals modest. This *Letter* proposes a few strategies for observing the broad-line regions of AGNs with nulling interferometers, emphasizing the benefits of coupling these instruments with moderate-resolution spectrographs.

2. Possibilities

Nulling interferometers possess useful coronagraphic capabilities on scales smaller than their beamsizes. Each pointing of such an instrument convolves its two-dimensional transmission function with the projection of the target onto the plane of the sky. In principle, we can extract information about the source on scales smaller than the nominal resolution element as long as we know the interferometer’s transmission characteristics accurately.

Active galactic nuclei are ideal for such experiments because their spectra depend on projected distance from the nucleus. For example, optical long-slit spectroscopy of M87 with the Faint Object Camera on HST has revealed that its emission lines obey a nearly Keplerian rotation law to within 200 mas of its nucleus, where the projected rotational velocity is $\sim 600\text{ km s}^{-1}$ (Marconi *et al.* 1997; Macchetto *et al.* 1997). In the coming years, the Space Telescope Imaging Spectrograph will yield rotation curves on similar scales for a number of other nearby galactic nuclei.

Spectroscopic instruments with significantly higher spatial resolution will be needed to probe the velocity fields within distant quasars. Reverberation mapping experiments can provide information about AGNs on tiny scales of light days to months (e.g. Korista *et al.* 1996), regardless of the source’s distance, but the interpretation of this information can be ambiguous (Done &

Krolik 1996; Chiang & Murray 1996). In addition, the long variability timescales of distant quasars, owing to both their larger sizes and cosmological time dilation, render reverberation mapping of high- z objects impractical. Nulling interferometry, combined with spectroscopy, might be our best hope for weighing high- z black holes within the next decade.

2.1. Combining Spectroscopy with Nulling

Consider a nulling interferometer with a baseline B operating at a wavelength λ , and let δ be the angular distance between a given point on the sky and the locus of the symmetry plane. The transmission function of a such two-element interferometer is $T(\delta) = 1 - \cos \delta/\delta_0$, where $\delta_0 \equiv \lambda/2\pi B$. For an optical instrument like SIM with a 10 m baseline, $\delta_0 \approx 1.6$ mas and $T(1 \text{ mas}) \approx 0.2$, whereas the transmission of a point source directly on the null is $\sim 10^{-4}$ (Allen *et al.* 1997).

Simplistically we can picture an AGN as a pointlike continuum source surrounded by an extended line-emitting region. If we could aim a nulling interferometer directly at such an idealized AGN, the continuum signal would cancel, but off-axis line emission would leak through the interferometer. A spectrograph mounted on the interferometer would record only an emission line with a strength depending on the size and shape of the line-emitting region.

A single pointing of such a device at an AGN would thus tell us immediately the extent of the line-emitting region relative to the interferometer’s beam. Comparing the total flux of an emission line (F^{tot}) measured through a single-element system with that measured through a nulling interferometer (F^{null}) places a lower limit on the region’s size: $\delta > \delta_0 \cos^{-1}[1 - (F^{\text{null}}/F^{\text{tot}})]$. The continuum level would respond to the extended background from stars in the host galaxy and perhaps some scattered continuum light from the nucleus.

Modulations in the line flux transmitted through a rotating interferometer would echo the symmetry of the line emitting region. A linearly extended region, for example, would produce a line-flux signal that cycles from minimum to maximum and back twice during one complete rotation of the instrument. If the so-called “unified models” of AGNs are correct, the degree of azimuthal structure detected in this way should correlate with the inclination angle of the obscuring torus. Such information could also reveal whether the line emission comes from a disk or torus perpendicular to a jet or from entrained gas parallel to the jet itself.

2.2. Probing Milliarcsecond Velocity Structure

Assuming that a black hole of mass $(10^9 M_\odot)M_9$ drives the activity within any given active galaxy or quasar, we can easily compute the angular size θ of a $(1000 \text{ km s}^{-1})v_{1000}$ Keplerian orbit

around the central engine. Figure 1 gives the angular sizes of such orbits as functions of redshift z and density parameter Ω for various values of the parameter combination $M_9 h_{75} v_{1000}^{-2}$, where h_{75} is the Hubble constant in units of $75 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Because the Eddington luminosity of a quasar is $(\sim 10^{47} \text{ erg s}^{-1}) M_9$, the velocity fields around the most luminous quasars should exceed 1000 km s^{-1} at projected distances of 1 mas, no matter what the redshift. A nulling interferometer attached to a spectrograph of moderate resolving power ($R \equiv \lambda/\Delta\lambda \gtrsim 300$) can therefore constrain the velocity field at the outskirts of the broad-line region around any sufficiently luminous quasar.

If the velocities of broad-line emitting clouds are completely random or if the line-emitting gas flows out in a wind that reaches its terminal velocity within the core of the null, we would expect the widths of the emission lines seen through an interferometer to match those seen through a single-element telescope. On the other hand, if the line profile at a given projected radius depends on the gravitational potential of the nucleus, the width of the transmitted line should depend on the baseline of the interferometer. The following highly simplified model illustrates how the results of such an experiment might look.

Suppose that the target hosts a circularly symmetric emission-line region with a projected angular radius θ_{BLR} at which the Keplerian velocity is 1000 km s^{-1} , and consider two possible velocity laws. In the Keplerian case, the line profile at a given angular radius θ is

$$f_{\text{Kep}}(v, \theta) \propto \exp \left[- \left(\frac{v}{1000 \text{ km s}^{-1}} \right)^2 \frac{\theta}{\theta_{\text{BLR}}} \right]. \quad (2-1)$$

And in the case of a uniform velocity law,

$$f_{\text{uni}}(v) \propto \int_0^{\theta_{\text{BLR}}} f_{\text{Kep}}(v, \theta) \theta d\theta, \quad (2-2)$$

so that at low spatial resolution the line profiles are indistinguishable.

The observed line profiles resulting from these velocity laws look markedly different after the light passes through a nulling interferometer. One effective way to visualize differences between the overall line profile (F_{ν}^{tot}) and the nulled line profile (F_{ν}^{null}) in each case is to divide F_{ν}^{null} by F_{ν}^{tot} . Whenever the velocity law is uniform, this quotient will be a horizontal line. A declining velocity law, such as f_{Kep} , will show a peaked quotient, and the quotient for an accelerating flow should rise away from a minimum at 0 km s^{-1} .

Figure 2 illustrates the quotient $F_{\nu}^{\text{null}}/F_{\nu}^{\text{tot}}$ for a few selected parameter sets. The surface brightness $I(\theta)$ of the emitting region decreases as θ^{-2} , so that each logarithmic interval in θ contributes a similar proportion of flux. We truncate the outer radius of the emitting region at $\theta_{\text{BLR}} = \delta_0$ and $2\delta_0$, equivalent to observing the same region at two different baselines, one double the other. In order to avoid a divergence in flux, we truncate the emitting region at an inner radius of $0.01 \theta_{\text{BLR}}$. Solid lines show the resulting quotient profiles for $f_{\text{Kep}}(v, \theta)$, and dashed lines show the equivalent profiles for $f_{\text{uni}}(v)$. The dotted lines illustrate error estimates to be discussed in the following section.

The flux quotients in Figure 2 clearly reveal several basic characteristics of the underlying models. Models with Keplerian velocity laws produce pronounced peaks, indicating a decline in velocity dispersion with radius. When $\delta_0 = \theta_{\text{BLR}}/2$, we find $F^{\text{null}}/F^{\text{tot}} \approx 0.19$, indicating that the transmitted emission comes from a characteristic radius $\gtrsim 0.31 \theta_{\text{BLR}}$. When $\delta_0 = \theta_{\text{BLR}}$, we find $F^{\text{null}}/F^{\text{tot}} \approx 0.05$, indicating a characteristic transmission radius $\gtrsim 0.32 \theta_{\text{BLR}}$. In both cases, F_{ν}^{null} is nearly proportional to $\exp[-(v/1200 \text{ km s}^{-1})]$. Naively associating this velocity scale with the characteristic radius $0.32 \theta_{\text{BLR}}$ would yield an estimated central mass about half the true value. Invoking reasonable assumptions about $I(\theta)$, which will in general be unknown, would result in a more accurate but somewhat model dependent mass estimate.

3. Practical Matters

Techniques such as the one described here could potentially be used to weigh black holes within high-redshift AGNs if SIM or other nulling interferometers were equipped with spectrographs capable of resolving broad emission lines. If the velocity fields of broad-line regions turn out to reflect their gravitational potentials, as appears likely from HST observations of nearby AGNs (e.g. Marconi *et al.* 1997, Macchetto *et al.* 1997), interferometric measurements of these lines might tell us how close the luminosities of the central objects are to their Eddington limits, perhaps revealing how the black hole mass function in quasars changes with time. To be practical, these observations will have to overcome photon noise limitations of various sorts.

The current plan for SIM calls for 7 siderostats, each 30 cm in diameter, only two of which can be used simultaneously for nulling interferometry (Allen *et al.* 1997). A quasar with an AB magnitude of 17.5 at a particular wavelength ν produces a continuum photon flux at Earth of $F_{\nu}/h = 0.56 \text{ phot cm}^{-2} \text{ s}^{-1}$. Let the equivalent width of a line like C IV $\lambda 1550$ in the spectrum of such a quasar be $W_{\lambda}/\lambda = 0.1 W_{0.1}$. The total number of line photons impinging on two SIM siderostats in a $(1 \text{ day})t_{\text{day}}$ exposure would then be $(6.8 \times 10^6)W_{0.1}t_{\text{day}}$. Obtaining 10^5 counts in the spectrograph detector should be quite achievable, even with very modest assumptions about the instrumental efficiency.

The dotted lines in Figure 2 illustrate the 3σ error boundaries resulting from photon noise in $F_{\nu}^{\text{null}}/F_{\nu}^{\text{tot}}$, assuming that each exposure is long enough to yield 10^5 counts in the absence of nulling. The nulled spectra therefore comprise 5×10^3 counts and 2×10^4 counts for $\delta_0 = \theta_{\text{BLR}}$ and $2\theta_{\text{BLR}}$, respectively. At a resolution $R = 300$, the spectrograph divides the photons into 1000 km s^{-1} bins, seven of which cover the interesting part of the line. The precision of these seven points would be ample for determining the shape, amplitude, and velocity width of the flux quotient.

Ground-based interferometers with much more collecting area (i.e. Keck, VLTI) could conceivably be used to carry out similar experiments on infrared lines from much fainter sources

if there is a nearby calibrating source in the field bright enough for active fringe tracking. Bright quasars might be sufficiently luminous to serve as their own fringe-tracking sources; a K magnitude of 16 would probably suffice (von der Luhe 1997). Because the νF_ν spectrum of an AGN is generally constant to within a factor of a few, the photon flux within an interval of order ν is roughly proportional to ν^{-1} , making fringe tracking easier at longer wavelengths.

Projected space-based interferometers optimized for planet-finding (e.g. Angel & Woolf 1997) have larger mirrors than SIM and baselines longer by an order of magnitude. Such instruments could potentially study regions light days in size in the nearest active galaxies, complementing reverberation-mapping investigations, if they were engineered to work in the optical/UV as well as the IR. UV optimization would be unnecessary for studying high- z quasars because their strongest lines shift into the optical and intergalactic hydrogen obscures their UV light.

To compensate for the vibrational modes of such a large space structure the instrumentation will have to track source fringes with great accuracy (Woolf, Angel, & Burge 1997). The nulling precision required for planet finding ($\sim 10^{-3}$ in amplitude and phase, $\sim 10^{-6}$ in flux) is much stricter than that required for the types of observations described here ($\sim 10^{-1}$ in amplitude and phase, $\sim 10^{-2}$ in flux), but the typical brightnesses of quasars are $\lesssim 10^{-5}$ times those of nearby solar-type stars. Thus, interferometric studies of distant quasars would benefit from mirrors as large as possible – at least large enough to capture hundreds of photons within one vibrational period of the fastest significant mode.

4. Summary

This *Letter* has suggested how nulling interferometers might be used to probe the line emitting regions of AGNs on milliarcsecond scales. If instruments such as SIM are equipped with spectrographs with sufficient resolution, we will be able to constrain the velocity fields of line-emitting gas around luminous quasars throughout the universe. If these velocity fields are Keplerian, we might be able to weigh black holes at high redshifts, perhaps learning how their mass function evolves with time.

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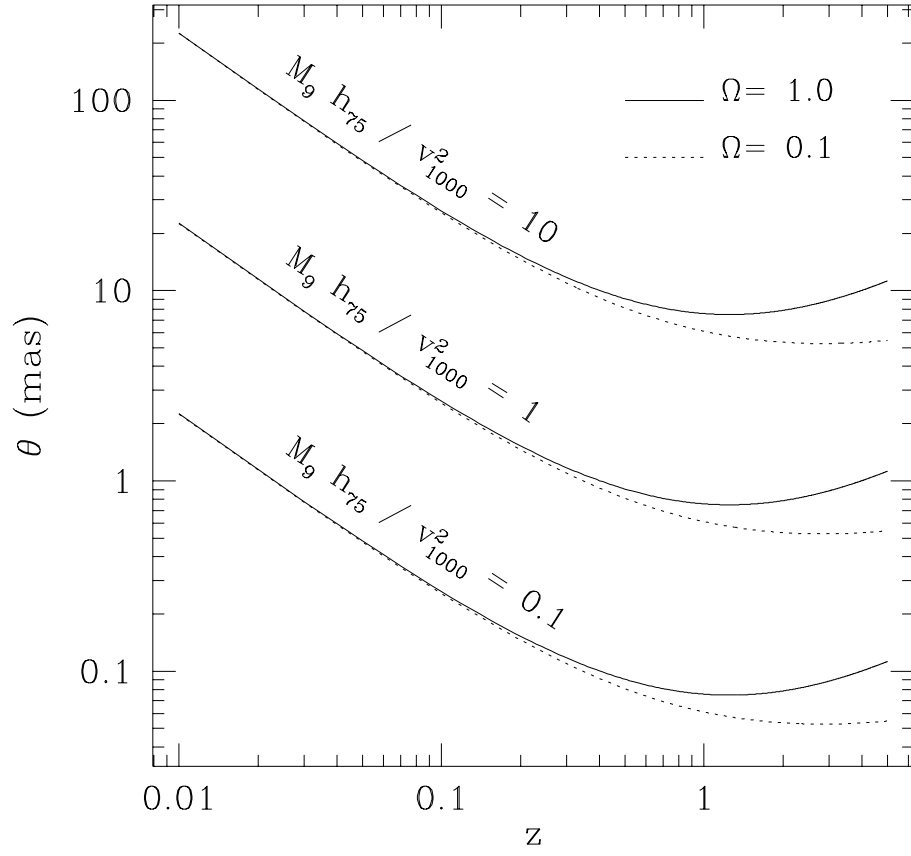


Fig. 1.— Angular sizes of Keplerian orbits. The lines show the angular sizes of circular orbits at speeds $v_{1000}(1000 \text{ km s}^{-1})$ around objects of mass $M_9(10^9 M_\odot)$, given a Hubble constant $h_{75}(75 \text{ km s}^{-1})$.

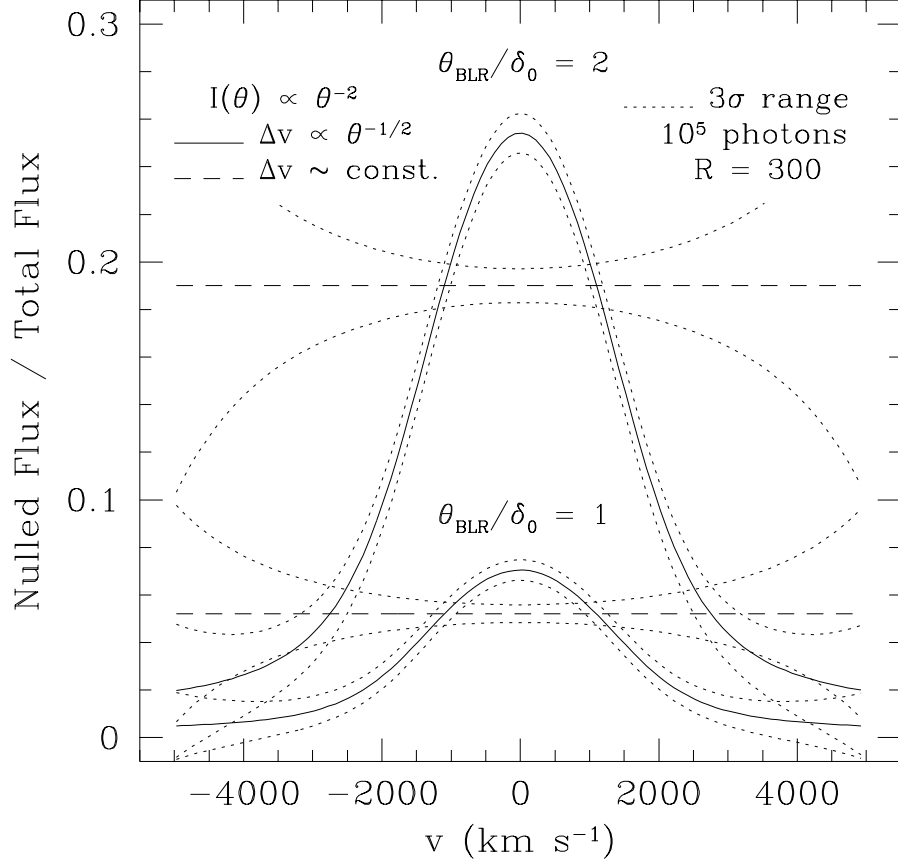


Fig. 2.— Relative transmission through a nulling interferometer. Solid lines illustrate the quotient spectrum $F_{\nu}^{\text{null}}/F_{\nu}^{\text{tot}}$ of an emission line region whose line profile at each radius is a Gaussian with a dispersion $\Delta v \propto \theta^{-1/2}$. The surface brightness I is taken to decrease with angular radius θ like θ^{-2} . The dashed lines show the quotient spectrum of a similar region with constant line widths. Dotted lines give the 3σ limits on photon shot noise at spectral resolution $R = 300$ when the integration time, assumed the same for all spectra, yields 10^5 counts in the integrated flux F^{tot} .